An Analytical Model to Predict the Response of Mounds Placed in the Offshore

by Magnus Larson and Bruce A. Ebersole

PURPOSE: An analytical model to predict the response of mounds placed in the offshore is presented, with the overall aim of providing a technique for the preliminary design of mounds subjected mainly to cross-shore sediment-transport processes induced by non-breaking waves. For example, offshore mounds created from dredged material can be used to protect sandy beaches by dissipating wave energy during severe storms or used as a source of beach nourishment. The model discussed here employs a diffusion equation to describe the mound response with respect to an equilibrium beach profile, where the diffusion coefficient is related to the local wave conditions at the mound. Analytical solutions to the diffusion equation are readily available provided the initial and boundary conditions are sufficiently simplified. Solutions yield characteristic quantities that are useful in preliminary design of offshore mounds when a number of project alternatives are considered and evaluated. The model provides quantitative information on how quickly a mound disperses under the influence of non-breaking waves at a particular site. With this information, one can estimate how quickly a beach may be nourished with material from the mound or how long the mound may protect the beach from severe storms (via attenuation of incident wave energy).

BACKGROUND: Recognizing the positive effects of bars for promoting beach growth and protecting beaches, a number of mounds have been constructed from dredged material (e.g., Zwamborn et al. 1970; McLellan 1990; Otay 1995; Foster et al. 1996). If a nearshore mound is intended to be stationary, it is referred to as a "stable" mound; whereas, if the mound is expected to move, it is called an "active" mound. Here, a mound is regarded as stable if the cross-shore sediment transport is small enough to only induce negligible changes in the mound shape (perhaps slight diffusion of the mound) according to some predefined criterion. Movement of an active mound might involve translation of its center-of-mass and/or significant dispersion. In the present note it is assumed that the mound is constructed from beach-quality sand, whether it is a stable or an active mound. In general, mounds need not be composed of such material, but the methods developed here are for sand mounds. Also, only mounds subjected to transport by non-breaking waves are discussed, and are alternatively referred to as offshore mounds. Lastly, the methods presented in this note are most applicable to mounds that are constructed as long, linear, shore-parallel bars where changes primarily take place in the cross-shore direction.

A brief summary of the sediment-transport model employed to describe the transport rate under non-breaking waves, taking into account wave asymmetry and gravity, is provided first. After certain assumptions are made, the sediment-transport equation is combined with the sand volume conservation equation to yield a diffusion equation for which many analytical solutions are available. Based on the analytical solutions, characteristic quantities are derived that summarize the main features of how mounds respond to the local wave conditions. Two applications (Silver Strand, California, and Cocoa Beach, Florida) are then shown, where the diffusion model was employed to describe temporal mound response using the diffusion coefficient as a fitting

parameter. The model was applied to two additional sites (Maunganui Beach, New Zealand, and Perdido Key, Florida), and a theoretically derived expression for the diffusion coefficient was validated by the four data sets. Finally, an example illustrating preliminary design of an offshore mound, using analytical solutions to the diffusion model, is discussed.

SEDIMENT TRANSPORT IN THE OFFSHORE: It is assumed that the transport in the offshore mainly is a function of onshore transport due to wave asymmetry (q_{ca}) and offshore transport due to gravity (q_{cg}) (compare Niedoroda et al. 1995). The latter transport is taken to be the product of the offshore-directed component of the sediment fall speed and a characteristic concentration in the bottom layer parameterized in terms of the energy dissipation in this layer. Following Larson *et al.* (1999a), the transport is written:

$$q_{cg} = \frac{C_d}{(s-1)^2(1-p)}\frac{2}{3p}f_d\frac{u_o^3}{g}\frac{\partial h}{\partial x} \tag{1}$$

where s is the specific gravity of the sediment, p the porosity, C_d an empirical coefficient, f_d the wave energy dissipation factor, u_o the bottom orbital velocity, g the acceleration of gravity, h the water depth, and x a cross-shore coordinate. The transport due to wave asymmetry is a function of the Shield's stress and the Ursell number (Larson et al. 1999a):

$$q_{ca} = C_a wd\left(\frac{1}{2}\frac{f_w u_o^2}{sgd}\right)^k\left(\frac{HgT^2}{h^2}\right)^m \tag{2}$$

where w is the sediment fall speed, d the median grain diameter, C_a an empirical coefficient, f_w a wave friction factor, H the wave height, T the wave period, and k and m empirical powers related to the dependence of the transport rate on the Shield's stress and the parameterization of the wave asymmetry, respectively.

A balance between these transport mechanisms yields an equilibrium beach profile (EBP; see Bruun 1954 and Dean 1977) shape for the offshore as discussed by Larson et al. (1999a). If an imbalance exists, there will be a net transport that may be computed from the difference between q_{cg} and q_{ca} according to:

$$q_c = q_{cg} - q_{ca} = \frac{C_d}{(s-1)^2(1-p)}\frac{2}{3p}f_d\frac{u_o^3}{g}\frac{\partial h}{\partial x} - C_a wd\left(\frac{1}{2}\frac{f_w u_o^2}{sgd}\right)^k\left(\frac{HgT^2}{h^2}\right)^m \tag{3}$$

where a positive value of q_c indicates offshore-directed transport. At equilibrium the profile shape is such that $q_{cg} = q_{ca}$. Thus, at a specific water depth h, the transport due to asymmetry may be replaced with the transport due to gravity at equilibrium yielding the following net transport:

$$q_c = \frac{C_d}{(s-1)^2(1-p)}\frac{2}{3p}f_d\frac{u_o^3}{g}\left(\frac{\partial h}{\partial x} - \frac{dh_e}{dx}\right) = K_c\frac{u_o^3}{g}\left(\frac{\partial h}{\partial x} - \frac{dh_e}{dx}\right) \tag{4}$$

Eq. 4 states that the transport is proportional to the deviation from the EBP slope at a specific depth. The proportionality coefficient is a function of the bottom orbital velocity cubed and the sediment characteristics. Introducing the transport coefficient K_c for the non-dimensional material-dependent quantities yields the right-hand side of Eq. 4.

ANALYTICAL SOLUTION TO OFFSHORE MOUND RESPONSE: The sediment transport relationship for the offshore (Eq. 4), in combination with the sand volume conservation equation, may in some cases be simplified to obtain analytical solutions for the profile evolution in this region (Larson et al. 1999b). Analytical solutions, although describing highly schematized situations, can be useful to derive quantities that provide characteristic time and space scales of profile response. These quantities could be employed for first-order estimates of profile response or for preliminary design of offshore mounds. If the transport equation is combined with the sand volume conservation equation, and certain simplifications are made, a diffusion equation will result for which many analytical solutions are available.

Assuming that the bottom orbital velocity is constant ($u_o = u_{oc}$) in the area of interest, and the response of the mound is described with respect to the EBP ($\boldsymbol{D}h = h - h_e$), yields the sediment transport equation:

$$q_c = K_c \frac{u_{oc}^3}{g} \frac{\partial \Delta h}{\partial x} \tag{5}$$

To compute the mound response, Eq. 5 is combined with the sand volume conservation equation given by:

$$\frac{\partial \Delta h}{\partial t} = \frac{\partial q_c}{\partial x} \tag{6}$$

where t is time. Substituting Eq. 5 into Eq. 6 yields:

$$\frac{\partial \Delta h}{\partial t} = \boldsymbol{e}_d \frac{\partial^2 \Delta h}{\partial x^2} \tag{7}$$

where:

$$\boldsymbol{e}_d = \frac{K_c u_{oc}^3}{g} \tag{8}$$

Equation 7 is formally identical to the diffusion equation and, as pointed out above, there are many analytical solutions available for this equation. Larson et al. (1987) presented many such solutions to the one-line model of shoreline change, which reduces to the diffusion equation under certain assumptions. They discussed several solutions related to the shoreline evolution resulting from the placement of a beach fill in the nearshore so that the shoreline becomes out of equilibrium with the wave climate. These cases have direct analogies with mounds (or, alternatively, dredged holes) in the offshore. Thus, under the assumption that Eq. 7 is valid to

describe the response of an offshore mound (or a dredged offshore hole), the solutions presented by Larson et al. (1987) for various beach fill configurations are applicable and will describe the mound (hole) evolution. Thus, the following general solution describes the evolution of a mound (hole) in the offshore:

$$\Delta h(x,t) = \frac{1}{2\sqrt{pe_d t}} \int_{-\infty}^{\infty} f(\mathbf{x})e^{-(x-\mathbf{x})^2/4e_d t} d\mathbf{x} \tag{9}$$

where $f(x)$ describes the initial shape of the mound (hole) and $\mathbf{x}$ is a dummy integration variable. This integral may be explicitly solved for simple mound configurations. For example, the evolution of a rectangular mound is given by the following solution (Larson et al. 1987):

$$\Delta h(x,t) = \frac{1}{2}\Delta h_o \left(erf(\frac{a-x}{2\sqrt{e_d t}}) + erf(\frac{a+x}{2\sqrt{e_d t}}) \right) \tag{10}$$

where $\mathbf{D}h_o$ is the initial mound height over sea bottom, a is half the mound width, and erf denotes the error function. If the initial height of the mound is given a negative sign, the solution will instead describe the filling up of a hole in the offshore.

CHARACTERISTIC QUANTITIES FOR MOUND RESPONSE: By non-dimensionalizing solutions to Eq. 7, the leading quantities may be identified, which can provide insight to the governing time and space scales. Also, these quantities will allow for comparison of the response of different mound designs. The evolution of an offshore mound, having an initial width a, will be governed by the non-dimensional time scale $t' = e_d t/a^2$. Two mounds having the same configuration but differing in size will display the same non-dimensional evolution in time, if appropriately scaled. Thus, the effect of various geometrical parameters on the evolution can be easily assessed by comparing the non-dimensional quantities. For example, the maximum non-dimensional height of two mounds with the same initial geometric shape will be the same after time t'. Translating this relationship into dimensional time yields:

$$\frac{t_1}{t_2} = \left(\frac{a_1}{a_2}\right)^2 \frac{e_{d2}}{e_{d1}} \tag{11}$$

where index 1 and 2 refer to the two different mounds. This equation shows that by doubling the width, a mound can withstand four times as long a period of the same wave action before experiencing the same relative decrease of the maximum height. The effect of the diffusion coefficient e_d is linear, but inverse, implying that a doubling of e_d causes the time for the mound to experience a certain reduction to be halved. This equation is useful for examining the evolution of mounds with different geometric characteristics exposed to the same wave climate.

By expressing e_d in terms of the local wave climate, the effects of the wave properties can be more easily assessed. Assuming linear wave theory,

$$\boldsymbol{e}_d = \frac{K_c}{8} \frac{H^3 g^2 T^3}{L^3} \frac{1}{\left(\cosh(2\boldsymbol{p}h/L)\right)^3} \qquad (12)$$

where L is the wavelength. Again, comparing two cases and equating the non-dimensional time t' gives:

$$\frac{t_1}{t_2} = \left(\frac{a_1}{a_2}\right)^2 \left(\frac{H_2}{H_1}\right)^3 \left(\frac{T_2}{T_1}\right)^3 \left(\frac{L_1}{L_2}\right)^3 \left(\frac{\cosh(2\boldsymbol{p}h_1/L_1)}{\cosh(2\boldsymbol{p}h_2/L_2)}\right)^3 \qquad (13)$$

In the case of shallow water, Eq. 13 may be further simplified to yield:

$$\frac{t_1}{t_2} = \left(\frac{a_1}{a_2}\right)^2 \left(\frac{H_2}{H_1}\right)^3 \left(\frac{h_1}{h_2}\right)^{3/2} \qquad (14)$$

Eq. 14 clearly illustrates the influence of the wave height and the water depth when comparing the evolution of two mounds of identical initial shapes. For instance, a wave climate with a characteristic height that is doubled causes a mound response in 1/8 of the time compared to the original conditions.

MODEL SIMULATIONS:

Example 1: Mound response at Silver Strand, California. Measurements taken in connection with the placement of a mound off Silver Strand State Park (Andrassy 1991; Larson and Kraus 1992) were used to validate the diffusion model. An EBP was determined in accordance with Larson et al. (1999a) and subtracted from the profile surveys to isolate the mound evolution. Wave measurements were carried out between January and May 1989 during which four surveys were taken (890119, 890215, 890315, and 890518, in YYMMDD format). The January survey was made just after construction of the offshore mound was completed. Subsequent surveys reveal how the mound evolved; most of the material moved onshore (Figure 1). During this period the wave climate was quite mild and no major storms were recorded. Thus, these data constitute an excellent set for testing the analytical model developed to predict beach profile change in the offshore under non-breaking waves. All profiles shown here were measured along Survey Line 5 extending across the central portion of the mound (Larson and Kraus 1992) where longshore effects were judged to be the smallest. The median grain size (d_{50}) of the placed material was 0.20 mm.

An optimum value for the diffusion coefficient, $\boldsymbol{e}_d$=15 m^2/day, was determined through fitting against the measured profiles. Figure 1 illustrates the agreement between the analytical model and the measurements. The analytical solution was obtained by superimposing a number of initially trapezoidal line segments as discussed by Larson et al. (1987). The surveys were carried out approximately 27, 55, and 119 days after the post-construction survey (used as the initial profile here). As seen in Fig. 1 the analytical solution produces a symmetric diffusion of the mound which is a result of assuming a constant diffusion coefficient (*i.e.*, u_{oc} is a constant). In a numerical approach $\boldsymbol{e}_d$ would be a function of water depth producing a more rapid diffusion in

shallow water that could describe the onshore migration of the mound and its skewed shape. In spite of this simplification the analytical solution captures the overall response of the mound quite well, and can be used to obtain reasonable estimates of quantities such as the decrease in the maximum mound height and the reduction in mound volume, within the original boundaries of the mound.
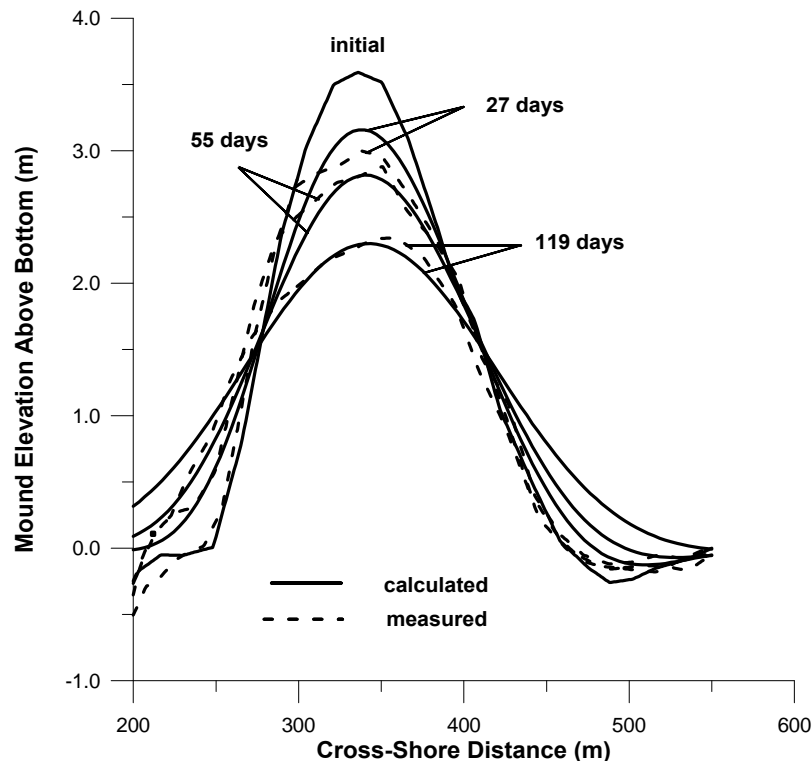

Figure 1. Measured mound evolution at Silver Strand, California, and predictions by an analytical solution based on a diffusion model

Example 2: Mound response at Cocoa Beach, Florida. Cocoa Beach near Cape Canaveral was used as "beneficial-uses" site for dredged material on three occasions between June 1992 and June 1994. The first placement was carried out in June 1992 in the northern half of the authorized site (approximately between survey lines 0 and +3500; see Larson et al. 1999b), whereas the second and third placements were conducted over longer time periods and broader areas.[1] Only data taken in connection with the first disposal were used here for further validation of the diffusion model. One survey was made immediately after construction of the mound, followed by two surveys 136 and 291 days after the mound placement. An EBP was determined in accordance with Larson et al. (1999a) and subtracted from the surveys to isolate the mound response. Survey line 1500 located in the central portion of the mound was used in the analysis and the median grain size (d_{50}) of the fill material was 0.14 mm. No wave measurements were carried out in connection with the profile surveying, but hindcasted waves showed that the mound was mainly exposed to non-breaking waves during the measurement

[1] Personal Communication, 1998, R. A. Wise, Research Hydraulic Engineer, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

period (also numerical simulations demonstrated that the transport due to breaking waves was negligible at the mound; see Larson et al. 1999b).

Figure 2 displays the agreement between the analytical model of mound evolution and the measured profiles. The diffusion coefficient was determined to be 8 m^2/day, which produced a satisfactory description of the mound response. As for the Silver Strand mound, the analytical model predicts some seaward diffusion not observed in the measurements due to an overestimation of e_d in this region. However, the overall evolution of the mound is well described by the analytical solution, creating confidence in the simple diffusion model for first estimates of how the mound would respond.
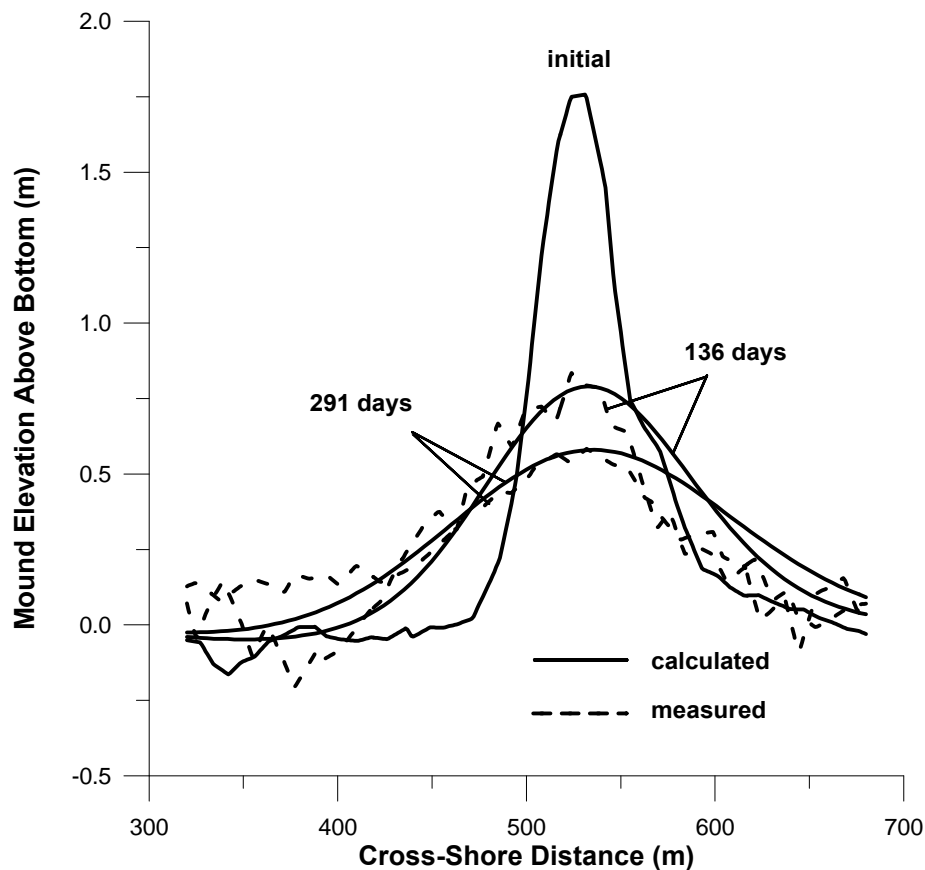

Figure 2. Measured mound evolution at Cocoa Beach, Florida, and predictions by an analytical solution based on a diffusion model

Example 3: Dependence of mound diffusion on wave conditions. In order to use the analytical model for preliminary design of offshore mounds it is necessary to estimate the diffusion coefficient. Although relative comparisons can be made based on the characteristic quantities presented earlier (e.g., Eqs. 13 and 14), it is often of interest to quantify the temporal evolution of a mound. However, the number of data sets on mound evolution which are suitable for determining e_d are limited. Besides the two previously discussed data sets (Silver Strand and Cocoa Beach), two other data sets were identified and used for analysis of e_d. These two mounds were located at Maunganui Beach off the coast of New Zealand (Foster et al. 1996) and at

Perdido Key, Florida (Otay 1995; Work and Otay 1996). Analysis of data from these two sites produced e_d = 25 and 1 m^2/day for Maunganui Beach and Perdido Key, respectively. Thus, a wide range of e_d-values was obtained in the analysis, which is expected considering the wide variety of conditions that prevailed at the different sites.

The representative wave quantities at Maunganui Beach were estimated based on various data sources which reported results of wave measurements off the New Zealand East Coast (Table 1 in Foster et al. 1996; straight-forward averaging was employed to obtain the representative wave quantities). However, Foster et al. (1996) pointed out that the data records did not contain many storm events implying that the wave height might have been somewhat underestimated. At Perdido Key, wave measurements were made at two wave gages, where the longest record encompassed a 4-year period. Mean wave quantities reported by Otay (1995) were used to compute the values employed here. The mean significant wave height and mean wave period obtained at the different sites were used as input to calculate the significant wave height ($H_{s,m}$) and associated bottom orbital velocity ($u_{oc,m}$) at a location corresponding to the initial maximum mound height (having the associated water depth h_m). Thus, all wave quantities employed in this study were measured or hindcasted for the period when the profile surveys were carried out, except Maunganui Beach which relied on more general estimates of the wave conditions. Table 1 briefly summarizes the environmental conditions and sediment characteristics at the four different sites.

Table 1.
Environmental Conditions

Site	$H_{s,m}$ (m)	T_a (sec)	h_m (m)	$u_{oc,m}$ (m/sec)	d_{50} (mm)
Silver Strand	0.78	8.7	3.8	0.59	0.20
Cocoa Beach	1.26	8.8	4.7	0.84	0.14
Maunganui Beach	1.33	9.0	3.5	1.05	0.29
Perdido Key	0.55	6.3	3.8	0.39	0.30

Note: Subscript s denotes significant wave height. Subscript m denotes quantities taken at water depth corresponding to peak of initial mound.

Equation 8 gives a theoretical relationship for how e_d depends on u_{oc}, and Fig. 3 shows this relationship plotted for the analyzed data sets. Although the scatter is considerable, there is a marked trend and an indication that Eq. 8 provides reasonable predictions for e_d based on the mean local wave conditions. The bottom orbital velocity employed was calculated from the mean significant wave height at the peak of the initial mound during the measurement period. A least-square fit of Eq. 8 to the data points yielded K_c = 0.0024. Efforts were made to estimate K_c individually for each case and relate these K_c-values to various non-dimensional parameters including grain size, but no clear relationship could be established. The present data points are few and do not support adoption of expressions for e_d that are more complicated than Eq. 8. It is interesting to note that the mound at Silver Strand was placed on top of a natural bar, whereas the other mounds were placed further offshore where the profile depth was monotonically increasing with distance offshore. This may have contributed to the fact that the data point from Silver Strand somewhat deviates from the overall trend of the points in Fig. 3.
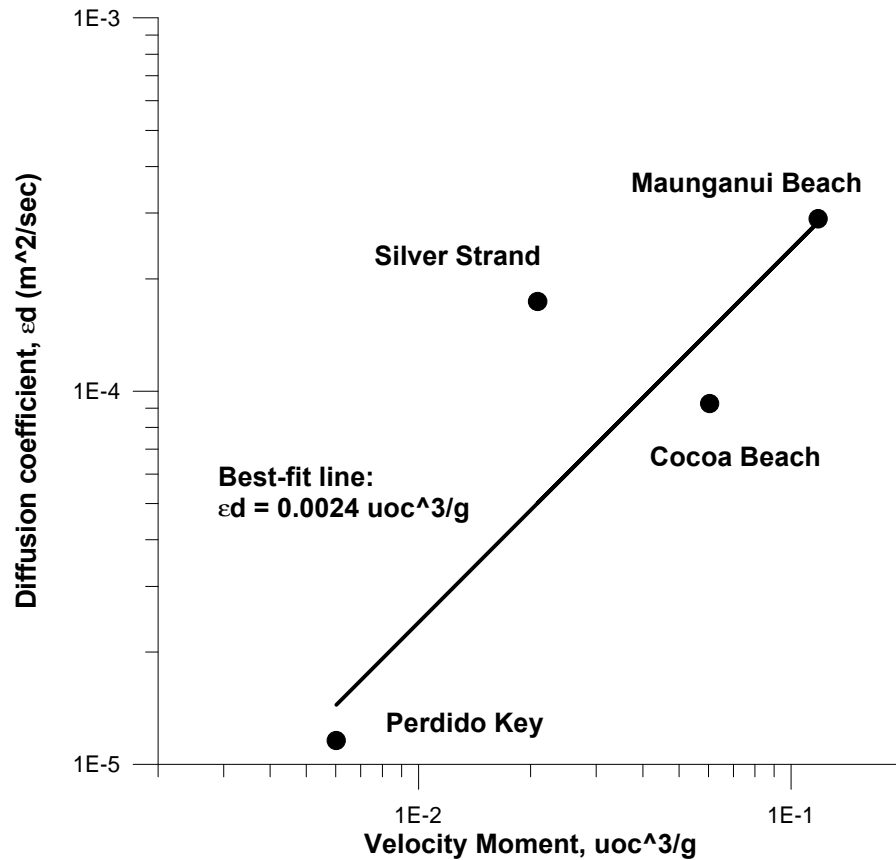
Figure 3. Diffusion coefficient for different placed mounds as a function of a velocity moment based on the bottom orbital velocity at peak of the initial mound (best-fit line also shown)

Example 4: Preliminary mound design. Based on the analytical solutions, preliminary design of mounds can be carried out and key parameters expressing the mound response can be estimated. It should be emphasized that the analytical solutions were obtained employing considerable simplifications, and the limitations of these solutions should be realized. However, reasonable results were achieved for the field sites investigated; and the solutions should provide acceptable first estimates of the mound response as long as cross-shore sand transport under non-breaking waves is the dominant transporting mechanism. Also, the prevailing wave and sediment conditions should not deviate too much from the field cases summarized in Table 1.

The solution presented by Larson et al. (1987) for a collection of line segments can be applied for any initial mound shape. Here, only the example of an initially triangular mound will be discussed (the solution for a rectangular mound is given by Eq. 10). Figure 4 illustrates the time evolution of the non-dimensional maximum mound height and non-dimensional mound volume for a triangular mound. Height and volume were normalized with their values at time $t = 0$, and the volume expresses the amount of material within the original boundaries of the mound, between $x = -a$ and a. With knowledge of the typical wave climate (mean significant wave height and period) and the dimensions of the mound (height and width), Fig. 4 can be used to estimate the height and volume after a certain time. Similarly, the water depth of placement can be optimized to achieve a specified spread of material (i.e., volume reduction) using the figure. To

simplify the estimation of the diffusion coefficient when applying Fig. 4, Fig. 5 was constructed using deep-water wave quantities and neglecting refraction. Thus, from the wave conditions in deep water e_d may be estimated at any water depth using Fig. 5.
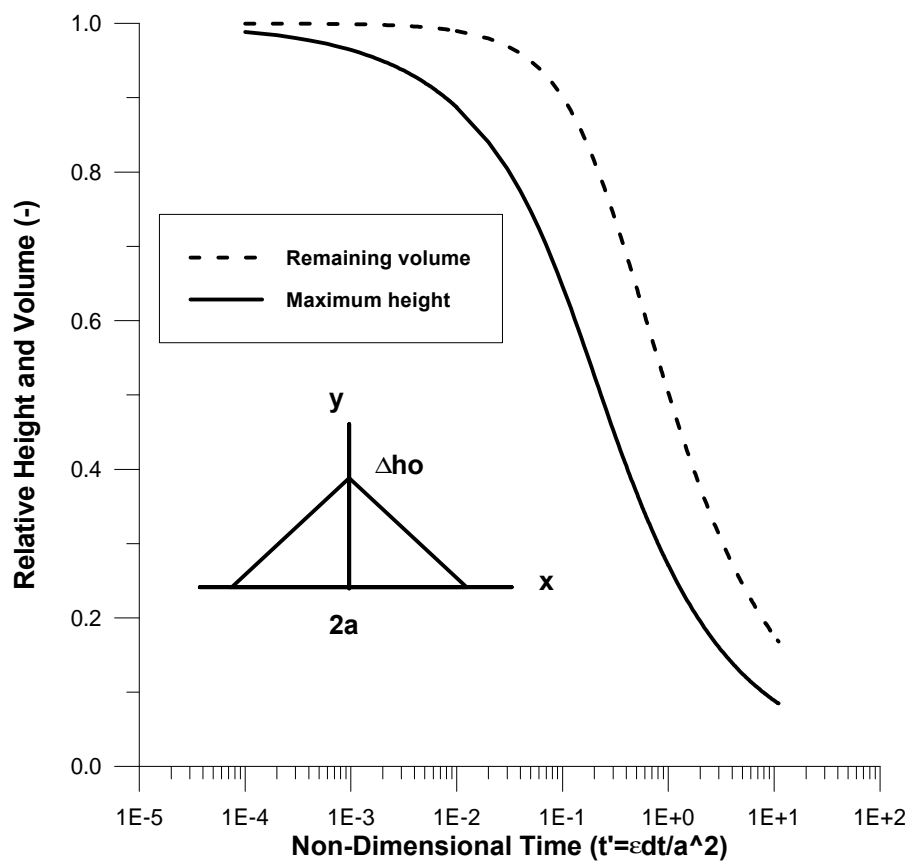
Figure 4. Time evolution of the relative height and volume for an initially triangular mound as a function of non-dimensional time
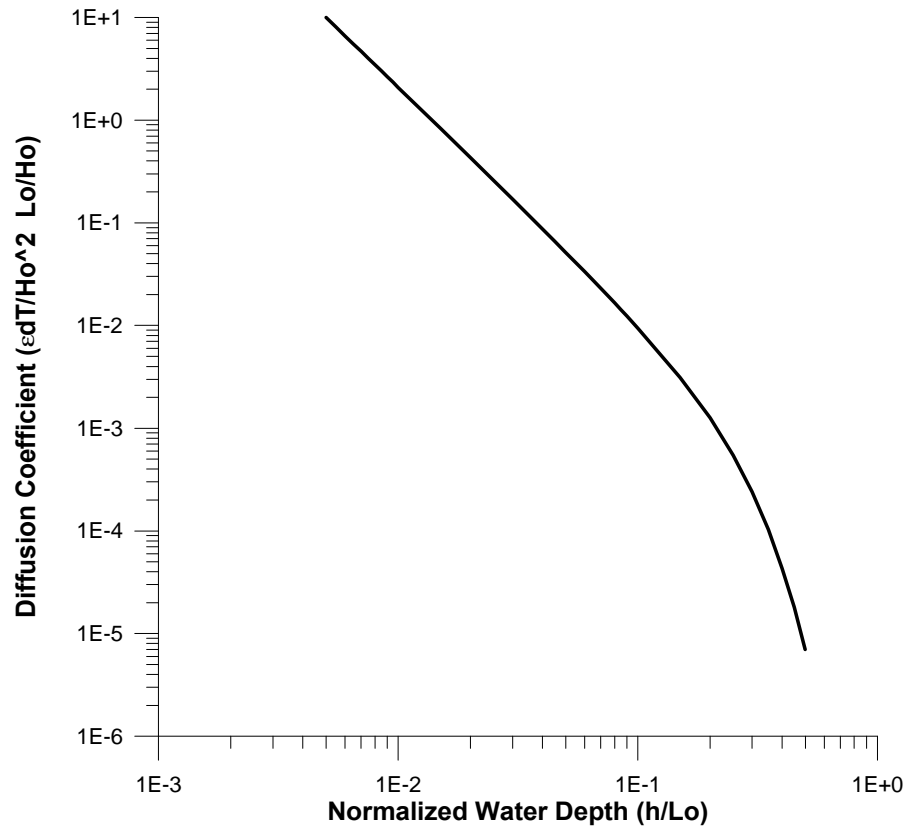
Figure 5. Diffusion coefficient as a function of water depth expressed in
non-dimensional form (normalized with deep-water wave quantities)

As an example, consider a typical U.S. East Coast wave climate with an average deep-water significant wave height of 1.0 m and an average wave period of 8 sec. Placing an initially triangular mound with the peak in $h = 4$ m water depth gives $h/L_o = 0.04$ and $e_dT/H_o^2 L_o/H_o = 0.087$ from Fig. 5. Thus, e_d is calculated to be approximately $1.1 \cdot 10^{-4}$ m^2/sec (=9.5 m^2/day). Assuming an initial mound width of 100 m (*i.e.*, $a = 50$ m), the mound response after 1 month can be determined from Fig. 4. The non-dimensional time is given by $t' = 9.5$ $30/50^2 = 0.11$. From Fig. 4 it is seen that the remaining volume (**D**V/**D**V_o, where **D**V is the mound volume and subscript o denotes the initial conditions) is about 90 percent of the volume placed originally and the maximum height is about 60 percent of the initial height ($\Delta h/\Delta h_o$). As previously pointed out, Fig. 4 is valid for an initially triangular mound. Other mound shapes (e.g., rectangular) might display quite different evolution, especially regarding the decrease in Δh. However, the evolution of the remaining volume, being an integrated quantity, is less sensitive to the initial mound shape. The analytical solutions describing the time response of the mound can be used to design both "stable" and "active" mounds, where the "stability" (or "activity") of the mound should be defined in terms of changes in geometric mound properties over certain time scales.

Finally, it should be pointed out that the solutions discussed here are equally applicable for holes ("negative" mounds) as long as the assumed mechanisms controlling the sand transport and hole response are the same.

ADDITIONAL INFORMATION: Questions about this CETN can be addressed to Mr. Bruce A. Ebersole (601-634-3209, Fax 601-634-4314, e-mail: *ebersob@wes.army.mil*). Thanks to the reviewers of this CETN, Messrs. Jarrell Smith and William Curtis.

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